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Inferring Number, Time, and Color Concepts from Core Knowledge and Linguistic Structure

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INTRODUCTION

Only humans acquire concepts like *infinity, democracy, hour*, and *belief*. We often express these concepts via language and use them—and many other abstract concepts—to explain, predict, and engineer the physical world, as well as to interpret the behaviors of humans and other creatures. Abstract concepts like these are interesting because, while they provide useful tools for describing worldly objects and events, their content is difficult to glean solely from perception of the world. Consider the case of number: Objects in a set of *seventeen* do not themselves exhibit the property of "seventeen-ness"; also, instances of *infinity* can never be experienced directly. Similarly, *electrons* and *beliefs* cannot be perceived by the naked eyes or ears but are inferred from complex constellations of events and behaviors. These observations—and more generally facts regarding our conceptual understanding of biology, mathematics, physics, and the cosmos—are the central challenge that any complete theory of human knowledge and its origins must explain. How do humans acquire abstract ideas that are not transparently reducible to perceptual content, but which can nevertheless explain and predict events that we perceive via our senses?

A complete account of the origin of human concepts will ultimately have many aspects, involving multiple levels of explanation. Some explanations will appeal to diachronic processes of change, including the cultural transmission of knowledge, the biological evolution of species, and the development of human artifacts and technology. Other

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explanations of the origin of human concepts focus on the problem of learning: how individual entities—like human children—are able to use evolved learning mechanisms to acquire information, whether directly from perceptual experience or via cultural transmission, and then go beyond this acquired information to innovate and create new ideas and systems of representation.

We know that the origin of some mental representations can be explained almost entirely by processes of biological transmission and natural selection. This point is perhaps least controversial when we consider nonhuman species (see Carey, 2009, for discussion). For example, different animal species are innately predisposed to use different sources of information to guide navigation and seasonal migration. Some species navigate by the stars, some by the sun, some using the Earth's magnetic field, while others by acquired mental maps that rely on visual and olfactory landmarks. Furthermore, the precise ways in which such cues are used by animals can differ from one species to the next: Tunisian ants are sensitive to patterns of polarized light in the sky (Müller & Wehner, 1988; Vowles, 1950), while birds like the Australian silvereyes use sunlight to modulate their interpretation of magnetic information (Wiltschko, Munro, Ford, & Wiltschko, 1993). Salmon rely on magnetic cues to navigate, completely independent of sunlight (Quinn, 1980), while birds like the indigo bunting navigate by the North Star, which they identify within a maturationally circumscribed developmental window (Emlen, 1975; see Carey, 2009, for review).

Other forms of mental representations are clearly *not* innate in this way. They are acquired by only some individuals within a species, sometimes according to very protracted developmental timelines. For example, human children take many years to acquire adult-like meanings for words that represent time, number, color, space, and biological concepts like *alive* and *dead*. Clearly, any computational theory of how these concepts are acquired must posit basic units of information, or primitives, which serve as inputs to learning, as well as a learning mechanism (or set of mechanisms) which operate over these primitives, whatever they are. The difficult question is how a learner might use such primitives—which to be useful to learning must ultimately interface with experience—to acquire concepts as abstract as *belief* or *infinity*, which cannot be defined in terms of purely perception.

An extreme empiricist solution, like that found in the writings of John Locke (1690/1964), is to argue that abstract concepts are acquired via iterative processes of association and abstraction, beginning with primitives that have sensory content. In contrast, an extreme nativist solution is to propose that abstract concepts are either wholly innate or composed from relatively abstract, specialized primitives, with little assembly required (e.g., Fodor, 1998). Both types of account are "building-block" models of conceptual development. Empiricist building blocks are like "old" LEGO, which primarily takes the form of simple bricks that can be combined in a large number of ways to create an almost unlimited number of different structures (Figure 7.1). As noted on Brickipedia, just six standard eight-stud pieces of LEGO can be combined in over 915,103,765 ways, and seven bricks can be combined in 85,747,377,755 ways.[1] These

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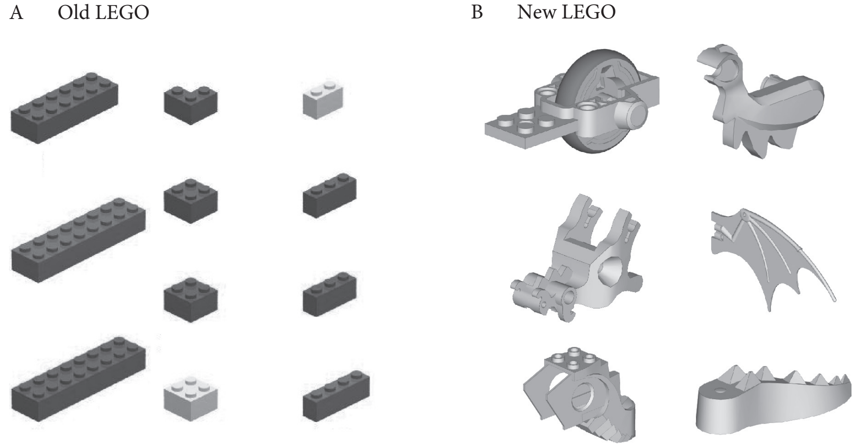

FIGURE 7.1 Examples of blocks from (**A**) old LEGO and (**B**) new LEGO.

building blocks are simple to manufacture and can be used to build nearly anything (given enough time and space), but they require significant instructions and input from the environment (the LEGO user) to create complex objects. In contrast, "new" LEGO—the nativist alternative—is sold in sets of highly specialized pieces, which are designed to create specific objects and to carry out highly specialized functions (e.g., a dragon composed of ~20 pieces, including prefabricated limbs, wings, etc.). These blocks are much more difficult to manufacture (just as eyes take time to evolve) and are much more constrained in function, but they allow users to create highly sophisticated objects with very little input.

Both building-block models suffer from the same basic limitation: At their extremes, both models offer little more than a promissory note regarding the problem of how abstract ideas might interface with perception of the world in the service of learning. In each case, the "bricks" or primitives that make up mental representations must be placed into correspondence with entities in the real world if they are to represent them. Empiricist models offer the advantage that the simplest building blocks are easily characterized by perceptual features (e.g., see Biederman, 1987), thus providing a natural story for how these blocks are linked to things in the world. However, these models suffer from the problem that it is difficult to see how concepts like *infinity* or *belief* could ever be defined in terms of collections of perceptual features; no perceptually defined LEGO-like model of *infinity* or *democracy* would appear to be forthcoming. In contrast, nativist models offer the advantage of providing clearly articulated models of how fully formed concepts could represent abstract content, since they are presumed to be specialized at the outset. Their problem is explaining how, in development, children might identify how these abstract representations correspond to experience of the world.

This basic tension sits beneath much current debate between nativist and empiricist accounts. As Martin Braine (1994) has argued, whereas nativist accounts generally focus

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on explanations of human universals, and "what is cognitively and linguistically primitive," they often neglect to account for processes of change and development and thus fail to bridge postulated primitives to plausible psychological learning mechanisms (e.g., that might link primitives to stimuli in the world). Meanwhile, empiricist models, by beginning with what are considered to be psychologically plausible learning mechanisms, often do not easily scale to account for the types of conceptual content that humans routinely acquire. This tradeoff in focus is surely one cause of the historical impasse between nativist and empiricist accounts. However, another problem may be with the building-block model itself, which assumes that complex concepts are directly composed of smaller units (whether new LEGO or old) and that this decomposition allows complex concepts to interface with lower-level perceptual representations. The problem is that such theories require the building blocks to be sufficiently abstract that they can combine to represent ideas like *infinity* and *democracy* but sufficiently concrete to make contact with the world of physical objects and events. It is possible that such a requirement is simply too tall an order for any complete theory of conceptual development.

An alternative to this class of building-block solutions, proposed by Susan Carey in her 2009 book, *The Origin of Concepts*, is to treat the problem of defining the content of concepts as somewhat separate from the problem of how they are acquired. For Carey, concepts like *seventeen* or *hour* are defined by their *inferential role*—that is, by the set of inferences that the concept is involved in or supports (Block, 1987; Carey, 2009; Harman, 1987). For example, it is part of the meaning of the word *seventeen* that it is equal to *sixteen plus one*. And *sixteen* can be identified as the number that is equal to *fifteen plus one.* And so on. However, Carey recognizes that on its own, such a theory cannot entirely explain how concepts get their content, since no network of inferential relations, however rich, can explain how individual concepts relate to our experience of objects and events in the world. Knowing that a blicket is composed of a toma and a pimwit tells us important information about blickets, but is useless for identifying blickets in the world, absent some concrete notion of what tomas and pimwits are. To address this problem, Carey (2009) makes the important move of anchoring an inferential role model to systems of what she and others call "core knowledge"—systems of innate input detectors, which generate primitive representations upon which an inferential role model can operate (e.g., Spelke, 2000). For example, in this view, concepts like *one, two,* and *three* are acquired via their correspondence to representations of objects in visual working memory, sometimes called "object-files" (Kahneman, Triesman, & Gibbs, 1992). Once these small number words are acquired, inferential role meanings can then be acquired, by noticing the relationship between the small numbers (i.e., $2 = 1 + 1$; $3 = 2 + 1$; $4 = 3 + 1$) and generalizing this relationship to numbers in the count list (i.e., for any number n the meaning of its successor is $n + 1$). Thus, whereas acquisition begins by associating small number words with perceptual representations of sets in the world, the meanings of number words—including *one, two,* and *three*—are ultimately defined by their inferential relations to other numbers, without requiring a direct link to perception at all (at

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least not as part of their core meanings; for discussion of how they might become linked, see Carey, 2009, 2010; Sullivan & Barner, 2012, 2014).

This account falls under the umbrella of a larger class of "bootstrapping" theories of development (Gleitman, 1990; Grimshaw, 1981; Macnamara, 1982; Pinker, 1984). Bootstrapping theories have in common the thesis that representations of one kind, say syntactic, are acquired on the basis of representations of another kind, say semantic (or vice versa). For Carey, bootstrapping involves constructing concepts that are defined by their inferential roles from representations provided by core knowledge, plus, critically, a placeholder system of linguistic labels. For number, the placeholders include numerals in the count list—for example, *one, two, three, four, five,* and so on. For time, they include words like *minute, second,* and *hour.* For color, they include *red, green,* and *blue.* As a first step in learning, children begin by learning some or all of the placeholder symbols in a domain and organizing them into a class of alternatives (see Tare, Shatz, & Gilbertson, 2008, for evidence that children learn to associate these words with their respective lexical classes early in development). Next, or perhaps in conjunction, they learn the meanings of a subset of these words by appeal to concepts provided by core knowledge—for example, object files. Critically, these meanings yoke the placeholder system to the child's experience of the world. Having acquired a few meanings in this way, the remaining meanings of symbols in the placeholder structure can be acquired via their inferential relations to one another, and in particular to the subset of concepts defined by core knowledge.

Often, metaphors are invoked to prime the intuition of how bootstrapping models like this might work. For Carey, the closest metaphor for her idea comes from Quine (1960), which inspires the term "Quinian bootstrapping": "The child scrambles up an intellectual chimney, supporting himself against each side by pressure against the others. Conceptualization on any considerable scale is inseparable from language, and our ordinary language of physical things is about as basic as language gets" (Quine, 1960; p. 93). According to this metaphor, words provide stable surfaces, which, when put in place, allow children to "ascend" to ever more complex and articulated representations of the world. Critically, the meanings in this metaphor are not contained within the bricks of the chimney themselves—this isn't a building-block model of conceptual learning. Instead, the content of each brick (or concept) is defined by its relation to other bricks in the structure, which in turn arises from the child's interaction with the sum of these surfaces.

In the following sections, we assess this model in three case studies. One of these, number, has been discussed at length already by Carey (2009), but it is useful to revisit because it offers a framework for understanding other domains and because certain important differences from Carey's account will arise in our discussion. In the two remaining sections, we discuss recent evidence from the study of time and color words. Our goal in exploring these three case studies is to inform word learning and conceptual development more generally, by describing how children might bootstrap abstract conceptual content by linking perception to placeholder structures and the inferential networks that they support. In doing so, we will test three basic predictions of the bootstrapping account:

1. **Placeholders and procedures should precede adult-like semantics**. According to the bootstrapping hypothesis, the meanings of many words are defined by their inferential roles (or place in a "theory"). Learning begins when children identify words that belong to a class of relevant alternatives—that is, a placeholder structure. In the case of number, this means learning the count list. For time, it means learning that *second, minute,* and *hour* all form a class. And for color, it means identifying words like *red, green,* and *blue* as alternatives. In each case, carving out the meanings of words involves learning the system as a whole and contrasting the words within that system to one another. Thus, in this hypothesis, knowledge of the placeholders should precede the acquisition of adult-like meanings.
2. **Adult-like meanings within a domain should emerge together**. To the extent that words get their meanings via relations to one another, rather than through independent associations to perception, meanings within a conceptual domain should emerge in near synchrony. For example, if *sixteen* gets its meaning in relation to *fifteen,* then learning the former should depend on learning the latter first. Likewise, words like *minute* and *hour* should emerge in synchrony to the extent that their meanings are spelled out in relation to one another. Finally, in the case of color, a child may not be able to learn the meaning of *red* until they learn labels for neighboring colors like purple, pink, and orange, such that these colors can be excluded from their meaning for *red.*
3. **Meanings should be anchored, but not defined, by perception**. According to inferential role models of meaning, many words within a domain should get their meanings chiefly through their relation to other words in that same domain, and not necessarily through perception. Thus, a final prediction of this theory is that, for many words, children should initially focus on discovering relations between words, rather than on their relation to perceptual representations—even if such associations are ultimately acquired by adults.

The case studies of number, time, and color are interesting tests of these predictions and suggest a relatively nuanced picture of how children acquire concepts. First, consistent with Prediction 1, we will argue that in each of the three case studies children begin by learning placeholder structures and identifying the basic dimension of content that these structures represent. Second, consistent with Prediction 2, we review evidence that adult-like meanings emerge in near synchrony in each case study, with some interesting exceptions. However, evidence regarding Prediction 3 reveals important nuance: As we show, words that represent number, time, and color differ substantially with respect to how

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their meanings relate to perception and when such relations are established. Empirical data suggest that children associate duration words like *hour* to perception *very* late in acquisition—by around age 6 or 7—only after they have learned their formal meanings (e.g., that 1 hour = 60 minutes). In the case of number words, a subset of words—such as *one, two,* and *three*—are anchored to perceptual representations from early in development, whereas larger number words (above 4) are very gradually associated with approximate magnitudes between the ages of 3 and 7. Finally, in the case of color, although children carve out color word meanings by drawing on relations between words in a placeholder structure, each word is nevertheless also associated with perceptual representations from the beginning.

The differences between these case studies suggest a general architecture for word learning that extends beyond the case studies of number, time, and color. Specifically, they lead us to conclude that each word—or class of words—differs with respect to its relative dependence on perceptual representations and inferential roles. Some words, like *red* and *blue*, while relying on placeholder structures, also depend heavily on perceptual representations to get their meanings. Other words, like *democracy* or *molecule*, have little to no relation to perception and get their meanings almost entirely from their role in a broader theory-like structure. Many words fall squarely between these extremes. For example, recent work suggests that the meanings of relatively simple words, like *cup, happy,* and *chair,* cannot be well described by building-block models of meaning but instead appear to be learned slowly, over many years, as members of broader conceptual networks (e.g., Gutheil, Bloom, Valderrama, & Freedman, 2004; Malt, Sloman, Gennari, Shi, & Wang, 1999). Still, despite these differences, the overarching lesson of these different case studies is that resolving the impasse between nativist and empiricist theories of conceptual development may involve eschewing a strict building-block model of concepts while allowing networks of concepts to be yoked to experience by some subset (and possibly all) of its members. Bootstrapping models accomplish this goal, by permitting both associative and inferential processes to operate in tandem, with differing roles across different domains of content.

NUMBER

In *The Origin of Concepts,* Susan Carey (2009) explores number word learning as a central case study of conceptual change. The basic facts to be explained by a theory of number word learning are generally of two types. First, there is the target state—adult knowledge of the natural numbers. Second, there are the developmental facts—the trajectory by which children appear to acquire this knowledge. The adult target state can be roughly described by the formal axioms spelled out 130 years ago by Giuseppe Peano and Richard Dedekind (though it goes without saying that few adults have explicit, formal, knowledge of these axioms, and no humans did until around the nineteenth century). In (1)–(4), a

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relevant subset of these axioms is described,[2] including the successor function and its application to all possible numbers, in (3) and (4):

(1) 1 is a natural number.
(2) All natural numbers exhibit logical equality (e.g., $x = x$; if $x = y$, then $y = x$, etc.).
(3) For every natural number n, $S(n)$ (the successor of n) is a natural number.
(4) Every natural number has a successor.

Critically, these principles establish 1 (or in some formulations, 0) as a primitive to which the successor function (in 3 and 4) applies to generate larger numbers, which themselves must respect (2), the properties of logical equality. The successor of 1, $S(1)$, is 1 + 1, or 2. The successor of 2, $S(2)$, is 2 + 1, or 3. And so on. In this sense, numbers get their meanings via their inferential roles—by their relations to other numbers and in particular the successor relation (for other early discussions of the logical foundations of arithmetic, see Frege, 1884/1980; Hume, 1778/2012; von Leibniz, 1704/1996). Consequently, if these principles are taken as a model of psychological competence, then the problem of acquiring the positive integers is one of acquiring (1) the primitive 1, (2) the principle of logical equality, and (3) the successor function, *inter alia* (though in some views this knowledge is taken to be wholly innate—e.g., Leslie, Gelman, & Gallistel, 2008; von Leibniz, 1704/1996).

Numerous studies have found that children acquire meanings for the words *one, two, three,* and sometimes *four* in a very gradual process without yet understanding how to count, but that the meanings of larger numbers are acquired in what appears to be a single step, as though via a sweeping inductive inference (Le Corre & Carey, 2006; Sarnecka & Lee, 2009; Schaeffer, Eggleston, & Scott, 1974; Wynn, 1990, 1992). First, sometime around the age of 2, most children (in the US) learn to recite a partial count list (e.g., *one, two, three, four,* etc.) without yet knowing what these words mean (Baroody & Price, 1983; Fuson, 1988; Gelman & Gallistel, 1978; Schaeffer et al., 1974). Next, they acquire an exact meaning for the word *one* (these children are often called "one-knowers"). Some 6 to 9 months later, they learn a meaning for *two* (becoming "two-knowers"), and after another long delay, *three*, sometimes followed by *four* (becoming "three-" and "four-knowers," respectively). Typically these children, collectively known as "subset-knowers" (since they know only a subset of the number word meanings), do not use counting to enumerate sets and cannot use it to count sets larger than 3 or 4. However, by many accounts, children have some form of epiphany between the ages of 3 and 4 and realize that when asked to provide a large number—for example, 7—they can use counting to find this amount (for discussion, see Davidson, Eng, & Barner, 2012). Although the precise timing of these stages varies across populations, the basic sequence has been reported across a variety of distinct linguistic and cultural groups (Almoammer et al., 2013; Barner, Chow, & Yang, 2009; Barner, Libenson, Cheung, & Takasaki, 2009; Davidson et al., 2012; Piantadosi, Jara-Ettinger, & Gibson, 2014; Sarnecka, Kamenskaya, Yamana, Ogura, & Yudovina, 2007).

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For our purposes, there are three critical points here that will inform our discussion of color and time. First, according to Carey (2009), the meanings of some number words are acquired by appeal to representations that can be transparently related to perception. Specifically, in her account, *one, two,* and *three* are acquired via their correspondence to representations of objects in visual working memory, which by many accounts exhibit a capacity limit, such that only three to four objects can be attended to at any given time (e.g., for discussion, see Alvarez & Cavanagh, 2004; Atkinson, Campbell, & Francis, 1976; Kahneman et al., 1992; Luck & Vogel, 1997; Todd & Marois, 2004). Second, in Carey's view, most number words are *not* acquired in this way, and arguably all number word meanings, once acquired, get their meanings entirely independent of perception via their inferential role—that is, in accordance with the principles stated in the Peano-Dedekind axioms. Finally, these inferential role meanings are acquired via an inductive inference over a predetermined set of alternatives, which in this case is supplied by the verbal count list. Children acquire this list before they acquire any meanings and use it as a structure to constrain inductive inference.

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There are many points of controversy at each step in this argument which we and others have discussed before (Barner & Bachrach, 2010; Barner, Chow, et al., 2009; Davidson et al., 2012; Gallistel, 2007; Laurence & Margolis, 2005; Rips, Bloomfield, & Asmuth, 2008). For example, it is highly unlikely that children fully grasp the successor function when they first become cardinal-principle (CP)-knowers and more likely that CP-knowers are initially executing a blind procedure (Davidson et al., 2012; Cheung, Rubenson, & Barner, under review; Wagner, Kimura, Cheung, & Barner, 2015). As a result, there is currently no reason to believe that children learn the logic of counting by detecting the successor relation among the small numbers and then generalizing this to larger numbers. Also, in her version of this bootstrapping story, Carey (2009) helps herself not only to innate object files but also to innate set representations like those required for describing the semantics of natural language (e.g., Link, 1983). A question raised by this proposal is therefore whether object files are needed at all (Gallistel, 2007). We believe that they may be, both to explain why early number word meanings are limited to small quantities, and also how specific set sizes could be identified in the learning process within the set-relational hypothesis space. As noted in previous work, when groups of objects are represented as collections, both infants and nonhuman primates are less likely to encode the quantities contained within them (see Barner, Wood, Hauser, & Carey, 2008; Wynn, Bloom, & Chiang, 2002). Thus, this type of set representation, which binds individuals together into a single representation, may need to be supplemented by something like object files in order to support learning early cardinal meanings. Leaving these matters aside, for the present discussion we would like to emphasize the central idea of Carey's hypothesis: how children might exploit the inferential relations between number words to acquire their meanings.

The data from number word learning conform to the two main predictions made by an inferential semantics theory like Carey's. First, *placeholders and procedures precede an*

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adult-like semantics. Sometime around the age of 2, children in the US begin to recite a partial count list without knowing what individual number words mean. Next, they begin learning the meanings of *one, two,* and *three,* one by one. Still, these children treat counting as a blind procedure for many months (or even years). Early accounts argued that counting is purely procedural until children become CP-knowers (e.g., Fuson, 1988, inter alia), while more recent work suggests that children do not acquire its full semantics—including an induction of the successor principle—until much later, as late as 6 or 7 years of age (Cheung et al., under review; Davidson et al., 2012; Wagner et al., 2015).

Second, the inferential role meanings that children ultimately acquire for numerals in the count list are *anchored, but not defined, by perception.* For Carey, large number words are yoked to perception, and thus to experience of the world, via the small number words (*one, two,* and *three*), which themselves get their content from object-file representations. However, once these links are made, meanings are subsequently spelled out in terms of inferential relations like the successor function (for a computational model that mimics this transition, see Piantadosi, Tenenbaum, & Goodman, 2012). Later in development, other perceptual systems, which also are not constitutive of number word meaning (Laurence & Margolis, 2005), become associated with number words—for example, the approximate number system (Condry & Spelke, 2008; Gunderson, Spaepen, & Levine, 2015; Le Corre & Carey, 2006; Sullivan & Barner, 2012, 2014; Wagner & Johnson, 2011).[3]

A final fact that is consistent with the predictions of an inferential role model like Carey's is that substantial aspects of number word learning involve holistic changes to the entire system. The strongest piece of evidence for this claim is the observation that whereas children learn *one, two,* and *three* one at a time, they appear to learn the meanings of larger number words all at once, when they become CP-knowers. However, as already noted, recent work adds nuance to this picture and suggests that whereas procedural knowledge of counting appears to be acquired in sweeping steps that apply to all numbers, children's logical understanding of numbers may actually emerge much later and in a more item-based way (such that they can infer the successors of small numbers like *five* years before they can infer the successor of larger numbers like *twenty-five*). Critically, these facts are not inconsistent with the inferential view. Critically, important aspects of knowledge do emerge in synchrony (i.e., the procedures that provide placeholder structures for learning). Also, when logical meanings for larger numbers are worked out, they are determined by relation to other numbers, albeit in an initially item-based manner.

These basic facts form the core evidence for the claim that number word meanings are acquired via a type of Quinian bootstrapping: Placeholder structures like the count list and the counting procedures support learning of relations between symbols within the structure. This inferential web is linked to perception via a subset of the structure's representations—those whose meanings are most readily verified via perception (i.e., *one, two, three*). Children learn these early meanings in parallel with empty procedures, and, through the repetition of procedures in relation to sets of things in the world, they notice semantic relations between words—like the successor function (Cheung et al., under review; Davidson et al., 2012;

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Wagner et al., 2015). It is these types of relations between words within the system which supply the meanings of the words. In the two following sections, we describe how similar processes explain the acquisition of words that describe time and color.

TIME

Time is an intrinsic property of our experience, but, moreso than number, it is an intangible property of the world. To deal with the abstract, ineffable quality of time, human cultures have developed complex systems to precisely measure, label, and keep track of it. These are systems that children struggle for many years to master (e.g., Friedman, 1986; Friedman & Laycock, 1989). We use an array of spatial artifacts such as clocks and calendars to represent time, and we encode time in language at many levels of representation, from verb tense to narrative structure. Along with acquiring grammatical tense and aspect, and conventions of storytelling, children learn several sets of time words that represent specific points or periods in time (e.g., *yesterday, Friday, last year*) and particular lengths of time or durations (e.g., *minute, week, century*). Given that such units of time cannot be directly seen or heard, how do children figure out what a word like *minute* refers to?

As we describe next, nonverbal representations of duration are available to children early in development, making it possible that they might begin their acquisition of time words by forming associations between terms that denote particular durations and approximate perceptual representations of duration. However, this is demonstrably not what children do. Instead, as with number words, children initially learn duration words almost entirely on the basis of their inferential role—that is, based on the relationships they have to other duration words in the lexicon. Consistent with the predictions of the Quinian bootstrapping model described earlier, we show that (1) children first identify duration words as a lexical domain and acquire a placeholder structure for this domain, with little to no information about the absolute durations denoted by each term, (2) adult-like meanings of these terms are not acquired until very late in development and emerge in relative synchrony as children receive direct instruction in their meanings in school, and (3) ultimately, these meanings are linked to perception of duration, but mappings between perceptual representations and words like *minute* are not formed until after the children learn the formal meanings of these terms, several years after the initial placeholder structure is in place.

Although units of time like an hour are not directly coded by sensory receptors, young infants are nonetheless able to represent elapsed time. For example, beginning in the first month of life, babies display conditioned autonomic responses (e.g., changes in heart rate or pupil dilation) yoked to temporal patterns in visual and auditory stimuli, indicating that they anticipate the arrival of the next stimulus after a learned delay period (Brackbrill, Fitzgerald, & Lintz, 1967; Clifton, 1974; Colombo & Richman, 2002). By 4 months they can be trained to discriminate auditory tones and visual events on the basis of their durations (Brannon, Suanda, & Libertus, 2007; Provasi, Rattat, & Droit-Volet,

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2011; vanMarle & Wynn, 2006). Like infants' ability to discriminate the approximate magnitudes of sets (see Lipton & Spelke, 2003), their ability to discriminate temporal intervals is governed by Weber's law (i.e., it is ratio-dependent). Also, like in the case of number, the precision of duration discrimination increases steadily over development and is not yet adult-like at age 8 (Brannon et al., 2007; Droit-Volet, Tourret, & Wearden, 2004; Droit-Volet & Wearden, 2001). Importantly, psychophysical studies of temporal perception in infants and children typically only involve stimuli and delay periods whose lengths are on the order of milliseconds to seconds, far shorter than the spans of time to which most of our commonly used duration words refer.

While relatively few studies have examined children's acquisition of time words, several similarities between time word and number word acquisition have been noted. These features of time word learning also conform to the predictions of a theory whereby children bootstrap inferential role meanings. First, although duration words like *minute* and *day* often appear in child speech as early as age 2 or 3, children's early uses of these terms are often far from adult-like (Ames, 1946; Grant & Suddendorf, 2011; Harner, 1981; Shatz, Tare, Nguyen, & Young, 2010). Children do not appear to acquire their adult-like meanings until years later, when they enter grade school (Ames, 1946; Grant & Suddendorf, 2011; Tillman & Barner, 2015). However, during this lengthy delay between the onset of production and the eventual adult-like comprehension of duration words, children nevertheless seem to infer that these terms all belong to a common conceptual domain and thus form a set of linguistic alternatives. For instance, when 4-year-olds are asked questions about duration (e.g., "How long does it take to eat breakfast?"), they generally respond using duration words in combination with number or quantity words (e.g., "10 hours"), despite not using them accurately (Shatz et al., 2010).

In accordance with the first prediction of the bootstrapping account, in addition to picking out the relevant domain to which all duration words belong, children learn the structure of the lexical domain prior to learning the formal meanings of individual words. For example, our recent work indicates that preschoolers not only infer that each duration term denotes a different duration but also learn which terms denote greater durations than others, that is, their rank ordering: *second* < *minute* < *hour* < *day*. Thus, at the age of 4, children are able to choose the term that denotes the longer duration more accurately than predicted by chance (Tillman & Barner, 2015). Importantly, however, these meanings lack information regarding the absolute duration denoted by each term or the proportional relationships among them (e.g., that a minute is 60 times greater than a second). For example, children as old as 6 often fail to judge that "2 hours" is longer than "3 minutes," despite having a robust understanding of the number words involved and knowing that an hour is longer than a minute. This type of failure demonstrates a lack of understanding that the ratio between the length of a minute and that of an hour is greater than 2:3. Further, children are very poor at estimating the absolute and relative positions of these terms on spatial timelines representing duration, despite being relatively accurate with numbers and familiar events.

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Supporting the second prediction of the inferential role account, duration words appear to be acquired in relative synchrony, around the time when children enter grade school. Between the ages of 4 and 6, children's ability to rank-order duration words improves uniformly for *second, minute, hour,* and *day,* although there are differences in the accuracy of children's estimates for individual terms. Later, around the age of 6 and 7, a dramatic improvement in children's ability to answer direct questions about the meanings of these terms (e.g., "How many hours are in a day?") is found. Again, this change occurs across the board and is not specific to individual words. This suggests that learning to use the system as a whole—in conjunction with learning about clocks and calendars—is what supports children's acquisition of the individual words.

Finally, in accordance with the third prediction, children do not associate time words with perceptual representations of time until *after* their formal meanings have been learned in grade school. Furthermore, there is some evidence that children's knowledge of formal time word meanings actually *drives* their association with perception (Tillman & Barner, 2015). When both knowledge of formal meanings and age are included in statistical models of children's ability to accurately "space out" duration words on a time line, effects of age disappear, suggesting that performance is mediated by knowledge of the formal meanings. Thus, learning the approximate durations that correspond to time words may arise by learning the precise proportional relations between time words (e.g., that a minute equals 60 seconds) rather than via a process of directly associating time words with experiences of duration in the world.

In one sense, these results are not surprising: Much like number words, duration words get their meanings in relation to one another (1 hour = 60 minutes). For example, it is impossible to arrive at a fully adult-like understanding of *hour* without also understanding *minute*, which in turn cannot be understood without understanding *second*. Therefore, it is difficult to imagine a scenario in which inferential semantics would *not* play an important role in learning these words. However, data from children's acquisition of time words make a stronger point, which is that children learn an inferential role semantics for time words even before they know that this is the right approach to take. As in the case of number, although children *could* begin by associating words with approximate magnitude representations, they do not. These facts raise a final question: How is the conceptual domain of time words anchored to perception?

While more research is needed to address this question empirically, a Quinian bootstrapping account of time like the one Carey proposes for number might propose that children link the duration word placeholder system to perception via "small" duration words, such as *second*, with the same nonverbal representations of time that allow them to estimate and discriminate very brief durations in infancy. On this account, while *second* might be grounded in a nonverbal representation of time, larger-duration words need only be understood via their inferential relationships to *second*. Relatively early in development children might learn, via simple associative processes, the approximate duration of a second. At this point, although they might learn that seconds are shorter than

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minutes, they would still lack the adult-like meaning of minute, which depends on understanding both the positive integers (i.e., numbers up to at least 60) and the fact that a minute contains 60 seconds. Given an approximate meaning for *second* and training that each minute contains 60 seconds, children might construct an inferential role meaning for *minute,* which in turn could be used to learn *hour*, and so on.

To summarize, on analogy to the case of number, we have argued that children's acquisition of duration words conforms to three main predictions made by a Quinian bootstrapping model like Carey's (2009). First, knowledge of the placeholder system and the organization of words in that system precede the assignment of adult-like meanings to words. Children learn to represent time words as a lexical domain and then organize words in this domain according to their relative durations years before they acquire their adult-like meanings. Second, adult-like meanings for these terms are acquired in relative synchrony very late in development, as children receive instruction regarding their formal meanings in grade school. Finally, while the meanings of duration words like *minute, hour, day,* and *year* are ultimately linked to approximate representations of duration, they do not get their formal meanings from perception and do not become linked to perceptual representations of duration until after inferential role meanings have been acquired.

COLOR

As is the case with both time and number, color word acquisition begins with a placeholder system: Children understand that color words form a class of contrasting linguistic alternatives before acquiring adult-like meanings for individual words. While children do not necessarily memorize a list of colors before acquiring color words in the same way that they memorize the count list, they do respond to questions like "What color is it?" with a word from the color domain well before they are able to use color words with adult-like meanings (e.g., Pitchford & Mullen, 2003; Sandhofer & Smith, 1999; Wagner, Dobkins, & Barner, 2013). Recent evidence suggests that, in addition to knowing that color words form a class of lexical alternatives, children assign preliminary meanings to color words on the basis of color properties like hue, brightness, and saturation by the time they emerge in speech (Wagner et al., 2013; Wagner, Jergens, & Barner, under review). Nevertheless, adult meanings for color words take many additional months for children to identify and appear to only fully emerge when children have acquired the contrasting meanings of neighboring (perceptually close) color words. As we describe next, the meaning of each color word appears to be supplied not only by association with a focal hue but also by contrast to the other words the child knows—that is, according to its inferential role.

In their influential study of color word learning, Carey and Bartlett (1978) introduced a single new word—*chromium*—to children, in reference to an olive green tray. After a

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delay of 7 to 10 days, they then asked these children to identify the *chromium* tray, which some children did successfully. This study is widely cited for children's rather remarkable ability to "fast map" *chromium* to the perceptual experience of the olive green color after a single exposure. Accordingly, many accounts of color word learning since have assumed that fixing meanings for individual color words reduces to mapping linguistic input to preexisting perceptual representations. On these accounts, the real difficulty lies in recognizing that color words, as a class, refer to color properties (e.g., Kowalski & Zimiles, 2006; Sandhofer & Smith, 1999). Once the correct domain of meaning is identified, learning meanings for individual color words proceeds quickly, resembling an epiphany in which words are mapped to perceptually defined color categories, which children possess beginning in early infancy (e.g., Clifford, Franklin, Davies, & Holmes, 2009; Franklin, Pilling, & Davies, 2005). For example, according to Pitchford and Mullen (2003), "developmental studies have shown young children's perceptual color space is organized in a similar manner to that of the adult. . . . Thus, when children engage in the learning of color terms, they already possess color percepts on which color concepts can be mapped" (p. 53).

However, these accounts surely overstate the role that the perceptual system might play in defining color word meanings. As discussed by Carey (Carey and Bartlett, 1978; Carey, 2010), although a partial meaning of a color word can be learned in a single trial via a mapping to color perception, the *full* meaning of a color word can neither be determined by perception nor learned from a single exposure. As found by Carey and Bartlett (1978), a child could learn that *chromium* includes the hue olive green after hearing it used in reference to this color. However, color meanings are not exhausted by a single focal hue. To learn a word like *red,* the child must also know what is *not* red—that is, where the boundaries of the category lie. Critically, languages vary in both the number of words in their color lexicon and in how these words divide color space (Kay, Berlin, Maffi, Merrfield, & Cook, 2009). For example, Berinmo, a language spoken in Papa New Guinea, has only five basic color terms. This language fails to mark some color boundaries found in English while marking other boundaries that are not found in English. For instance, one Berinmo color word, *nol,* refers to greens, blues, and purples. Another, *wor,* refers to greens, yellows, oranges, and browns. Furthermore, while the location of color boundaries is related to the number of basic color terms a language has, there is also variability among languages with the same number of color words. For example, languages with four color words typically divide color space according to one of three different patterns (Kay et al., 2009).

Children entering the world must be prepared to learn any language and thus any set of color words. Accordingly, any complete account of color word learning must describe how children learning different languages converge on different category boundaries for their color terms. As noted by Carey and Bartlett (1978), a single instance of fast mapping cannot do this: "Included in the fast mapping is only a small fraction of the total information that will constitute a full learning of the word. The second phase, the

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long, drawn-out mapping, extended over the entire period of several encounters with the word" (p. 2). A sometimes overlooked finding in their study is that, after hearing the word *chromium* used to refer to an olive-colored object, only a few children correctly used this term in later tests. While many of the children did learn that *chromium* was a color word, they often overextended this new word to include objects that were green and brown. Children make similar systematic errors in their application of actual color words (Bartlett, 1978; Pitchford & Mullen, 2003). Consistent with Carey and Bartlett's account, recent work shows that children assign partial meanings to color words as soon as they begin using them in speech and perhaps earlier (Wagner et al., 2013; Wagner, Jergens, et al., under review) but that full adult-like meanings take years to master and appear to depend on knowledge of other, competing, color words. For example, Wagner et al. (2013) found that when children start producing color words, they assign partial meanings to them that are typically overextensions of their adult meanings. A child may use *red*, for example, to refer to red, orange, and yellow objects. As children acquire new terms (e.g., *yellow*), these new terms contrast with and constrain previously learned terms.

In the spirit of Carey (2009), this recent evidence suggests that in order to learn the meaning of a particular color word, a child must also learn the meanings of other color words, to determine where one color category ends and another begins. In this fashion, the meaning of each color word is determined both by its relation to perception and via its inferential relationship to other color words—a possible explanation for why adult-like meanings of color words often appear to arise in synchrony. Consistent with this, studies have shown that contrasting a new color word with one that is already in a child's color lexicon is an effective method of teaching children the new word (e.g., Carey & Bartlett, 1978; O'Hanlon & Roberson, 2006). Furthermore, O'Hanlon and Roberson (2006) found that children learned new color words more easily when they contrasted a new term with the child's previously used term for that color than when they contrasted a new term with any other color terms. These findings suggest that lexical contrast is helpful in training, not only because it places a new color word within the correct lexical class, but also because it highlights how the new term is related to existing ones—a central feature of inferential role models of meaning.

To summarize, like the cases of time and number, evidence from color word learning provides evidence for an inferential role model of meaning, whereby words like *seventeen, month,* and *yellow,* are first organized into their respective placeholder systems and then get their meanings via a gradual process of learning relations between words within each the relevant system. In the case of color, unlike time and number, each individual word may in fact be anchored perceptually. On the account just described, however, this anchoring falls short of exhausting color word meanings. The main difference between children and adults is not knowledge of how color words pick out focal colors but instead, knowledge of the scope of their meanings, and how words are restricted via their relationships to other words in the semantic domain.

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CONCLUSIONS

We began this chapter by arguing that one reason for the impasse between nativist and empiricist models of conceptual development is that theories of each type often assume a building-block model in which complex concepts are composed from simpler ones, just like LEGO pieces are used to build objects. The problem with such accounts is that they fail to explain either how simple building blocks combine to generate abstract concepts (e.g., on empiricist views) or how abstract concepts make contact with perceptual experience of the world (e.g., on nativist views). Following Carey (2009), we describe an alternative approach, where word meanings get their meanings in large part via their relations to other words in a placeholder structure. In some cases, like time and number, only a subset of words may be directly mapped onto perceptual representations, while others are related to the world via their place in the inferential system. In other cases, like color, each word is mapped to perceptual space, with referential boundaries restricted by competition among placeholder alternatives.

Data from the domains of number, time, and color support this model of development and show that, in each case, children begin by learning placeholder structures that constrain hypothesis testing and learning relations between words in these structures. However, the data also show that there is no single solution to the problem of how word meanings are learned. The interaction between perception and inferential role differs substantially across case studies, as do the relative contributions of these two factors in the early stages of word learning. Early in learning, perception plays a larger role for color than for number, and a larger role for number than for time. Color word meanings in particular are not articulated in terms of each other in the same way that number and time words are, even though children begin with learning a placeholder structure that constrains the construction of categories. This is not surprising, and in principle, there is no reason to expect that all concepts should get their content in the same way. Bootstrapping theories like Carey's (2009) make this point clear: Even within a domain, different concepts may initially get their content in different ways. For example, small number words may initially denote small sets of things, whereas larger number words get their content from the successor principle. Given this, it seems reasonable to expect cases in which all words in a domain make contact with core systems (much like color), as well as cases in which there is little to no connection to perception—for example, *democracy, infinity, belief*. As we see it, this question cannot be answered in a purely a priori manner, but is best addressed by investigations like those we have described here: by exploring the acquisition of concepts by children in development.

NOTES

1. Wikia—Brickipedia. LEGO. http://lego.wikia.com/wiki/LEGO

2. We omit a definition of equality (transitivity, reflexivity, etc.) and omit principles which rule out zero as a successor to a number and which define the successor function as an injection.

3. Critically, mappings between numerals and approximate number representations are massively flexible, such that a child's estimates for all numbers in their count list can be recalibrated by a single misleading association or even by the simple suggestion that the largest quantity they will encounter in an experiment is very large (e.g., 750) or very small (e.g., 75; see Izard & Dehaene, 2008; Sullivan & Barner, 2012, 2014). These facts are difficult to explain for accounts which argue that approximate magnitude representations might be constitutive of number word meanings (e.g., Gelman & Gallistel, 1992; Leslie et al., 2008). Besides the problem that the approximate number system is noisy and nonexact, there is the greater problem that particular numbers like *twenty* are mapped to different quantities depending on context—there are no absolute magnitude mappings, only relative magnitude mappings, created on the fly. Clearly, whatever the basis for the positive integers, it must provide meanings that are not only exact but also *absolute* and *stable*, such that *twenty* always means 20.

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